Development and Testing of Feedback Control System for Fused Deposition by Electrochemical Discharge (FDED) Process

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***Abstract*— Previous researches [1,2] on Fused Deposition through Electrochemical Discharge (FDED) process have revealed that the periodic instantaneous current wave form (ICWF) is the characteristic of the process and it is significant to maintain the nature of current waveform in order to have a deposition of consistent metallographic properties. The precise control of process parameters is essential for maintaining the current wave form. The standoff distance between electrodes (SOD) is the most critical parameter amongst all. Karnik, Ghosh and Shekhar [1] have shown that the piling up of metal occurring at the impingement zone during the deposition reduces the SOD resulting in higher current and higher rate of metal dissolution from the copper wire anode (tool). The higher metal dissolution from the anode eventually increases the SOD, resulting in lowering of current, the termination of discharge and reduction in deposition rate which leads to discontinuities in the deposition. The SOD, the deposition rate and current waveform could be maintained by controlling the instantaneous tool feed rate. In the present investigations, the instantaneous tool feed rate has been controlled in response to the feed back value of the ICWF as it indicates pile-ups as well as the instantaneous phase of the process. An algorithm using a combination of proportional and discrete event control to determine the tool feed rate has also been developed and tested to maintain the ICWF. The results demonstrate the effectiveness of the algorithm by revealing an increase in deposition rate and volume fraction of the deposition.**

***Index Terms*—Fused Deposition by Electrochemical Discharge, Feedback control, Discrete event control system, Proportional controller, Deposition rate**

I. Introduction

Karnik, Ghosh and Shekhar [1] have successfully investigated the effects of process parameters such as applied voltage, SOD and electrolyte flow rate on the deposition rate and deposition characteristics in FDED process. Karnik [2] has also analysed the periodicity and the nature of ICWF at different combinations of process parameters and correlated it with the different events occurring during FDED. A typical ICWF in FDED is schematically represented in Fig.1. As seen in the figure, the wave form is periodic in nature. During the time interval T_{ON}, the value of current is C_{AMP}. This current causes the electrochemical reactions which leads to the

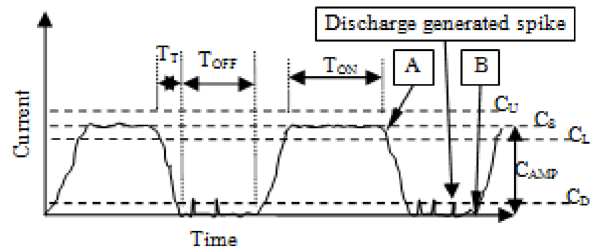

Fig. 1: A Typical current waveform of FDED

deposition of copper on the substrate and evolution of gases at both electrodes. T_{OFF} is the time interval in which the current is almost zero with a few current spikes. In this time interval the impingement zone is isolated from the electrolyte jet by the gas-vapour blanket, and a voltage gradient of the order of 10^6V/m is developed near the substrate. This leads to tiny, discrete discharges in the impingement zone indicated by the spikes shown in the T_{OFF} region [2]. The heat released during the discharge fuses the copper, deposited during 'T_{ON}', resulting in higher deposition rates and better metallographic characteristics such as volume fraction. T_T is the transition period where the value of current changes rapidly when the phase changes from T_{ON} to T_{OFF} or T_{OFF} to T_{ON}. This time interval is observed to be less than half a ms. The terms C_U, C_S, C_L, C_D, A and B will be explained later in the text. It has been observed experimentally by Karnik [2], that the nature of ICWF changes with the process parameters. Its frequency varies directly with the applied voltage and SOD. These parameters affect the average current in the cell which eventually affects the value of C_{AMP}, the duration of T_{ON} and T_{OFF}. The average current in the cell is directly proportional to the applied voltage and electrolyte flow rate where as it varies inversely with the SOD. An increase in T_{ON} or C_{AMP} would increase the electrochemical deposition. And a decrease in T_{OFF} would reduce the frequency of discharges. The ICWF demonstrates constant current nature between the applied voltage of zero to 80V, it is periodic above 80V and upto 200V. It becomes transient above 200V. With the frequency of ICWF, the frequency and amplitude of discharge generated spikes in the T_{OFF} region also increases. The discharges with high the energy input (VI) can erode the pre deposited metal by melting and evacuation. This is effectively the machining of the pre deposited metal.

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Hence, the ICWF is a potential characteristic of the process which can illustrate the effects of process parameters on the deposition rate and deposit characteristics. Additionally, it also indicates the instantaneous phase of the process as the current is plotted against the time. Hence the feedback of ICWF can be used to control one of the process parameters, if others are maintained constant. The most convenient parameter to control is the SOD since it can be maintained by monitoring the tool (wire) feed rate by varying the speed of the stepper motor which runs the gear box feeding the tool.

A. Limitations of open loop control system

In the open loop control system a constant tool feed rate is maintained for a combination of process parameters. The criterion for maintaining SOD, in this case, was to maintain the tool feed rate such that the wire tip remains flush with the tip of the nozzle. With this condition, the table speed (work traversal rate) determines the SOD as it controls the residence time of the nozzle at a location which in turn influences the metal pile up at that location. A metal pile up reduces SOD. By increasing table speed amount of metal pile up can be reduced but cannot be completely eliminated. The change in electrolyte flow rate also affects SOD, by correspondingly changing the wire dissolution rate. The high rate of wire dissolution leads to metal pile up where as the low dissolution rate leads to protrusion of wire beyond the nozzle tip. In both the cases SOD changes to change the average and instantaneous current in the cell. The electrolyte flow varies within a range due to the physical limitations of the set up. It is controlled by a flow of air under pressure supplied by a compressor. The pressure in receiver of compressor is maintained between 4 and 6kg/cm^2 using a pressure sensor. As the pressure varies within the range, there would be a corresponding change in electrolyte flow rate. This is especially experienced when the pressure is near the lower limit.

The effects of metal pile up on SOD and the process itself is illustrated in fig 2. In phase 1, a metal pile up starts forming in the impingement zone with discharge on top of it, reducing the SOD. The metal pile is shown to be concentric or in a vertical stack because of the residence time of nozzle. In phase 2, the increase in metal pile up reduces the SOD to increase current in the cell. This leads to powdery deposit and high intensity discharge at the top that fuses only the top portion of the metal pile up. The increase in current also leads to excessive electrochemical dissolution of the wire tip which recedes from the nozzle tip. The result is a properly deposited lower layer, a powdery metal accumulation in the mid layer and a top layer of fused metal which has no adherence to the lower layer. In Phase 3, the powdery layer of metal pile gets washed by the flowing electrolyte. This results in an increased SOD, very low current in the cell and termination of discharge. By the time jet reaches a nascent spot on the substrate due to the table movement, the wire also reaches the nozzle tip, since the wire dissolution rate was decreased owing to low current in the cell. This is shown in phase4 of Fig.2. These events go on repeating. The deposition in such situations was found to be dendritic and discontinuous and non adherent to the substrate as shown in Fig.3. It is obtained at 2mm SOD, 150V and 0.2mm/s table speed captured using a Carl Zeiss image analyzer model no: STEMI 2000c, with a Pixelink PL-A662 camera at 16X magnification. Thus it can be concluded that if the tool feed rate is constant for a particular combination of parameters, maintaining SOD becomes difficult which leads to low deposition rates, poor quality of the deposit and causes unavoidable variations in ICWF. Hence it was thought that a closed loop control to maintain SOD can be a solution to this problem with ICWF as an ideal feedback parameter. The instantaneous current values could be directly measured and fed back, using an Analog to Digital Converter (ADC), to control the speed of the stepper motor that controls wire feed rate.

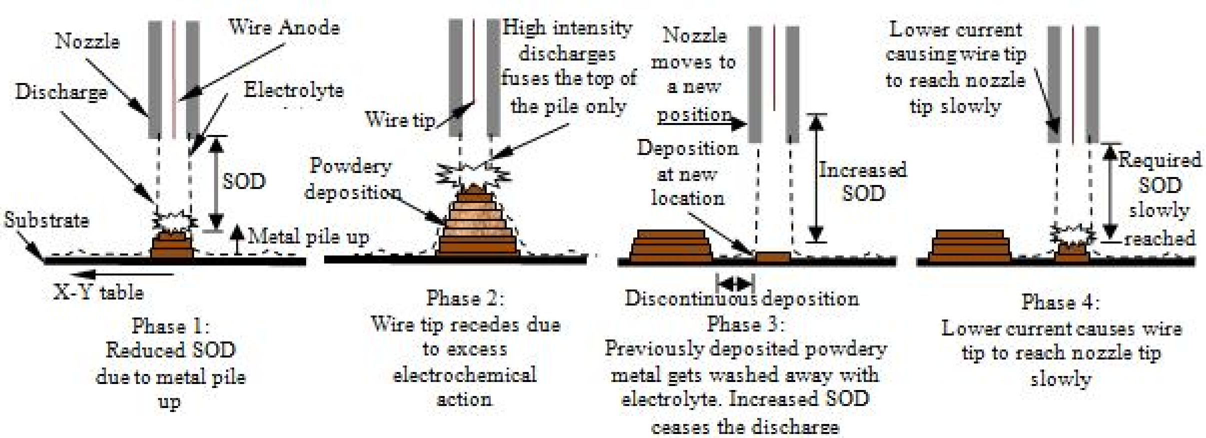

Fig:2 Schematic representation of effects of change in SOD due to pile ups- Phase by phase description

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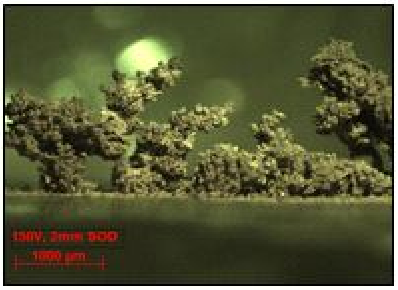

Fig : 3. Dendritic deposition at 2mm SOD, 150V, 0.2mm/s table speed

II. EXPERIMENTAL

The basic experimental setup is explained by Karnik [2]. Figure 4 explains the integration of ADC 0809 in the set up. It is connected across a 1 Ω resistor connected between the cathode substrate and the negative terminal of the power supply. The ADC has a medium range of resolution of 8 bits and is capable of giving a resolution of 3.9 mV per step in a measurement range of 0-1 V. Since the current in the circuit goes upto 300 mA, this resolution is thought to be sufficient enough for initial trials of feedback control. It is interfaced to the parallel port of the computer through 4 output pins for data transfer and three input pins for control and synchronization, via buffer IC 74ALS244. The buffer IC helps the computer to access the data from the ADC four bits at a time [3]. Thus the voltage measured across the 1Ω resistor, which is numerically equivalent to the current in the circuit as per ohm's law, is measured and fed back to the control system.

A. Operating range of process parameters

The range used for various process parameters is as follows, (a) SOD: 2mm, 3mm and 4mm.(b) table speeds: 1mm/s, 1.47 mm/s and 2mm/s. (c) The electrolyte is a solution of 0.8M $CuSO_4.5H_2O$, 0.9M H_2SO_4 and 5 ml of H_2O_2 in a litre of deionised water. (d)Electrolyte flow rate: 273 $mm^3 s^{-1}$. (e) The voltage range was from 10 volts before the discharge voltage upto 20 volts after discharge, all the trials spaced 10 volts apart from the preceding trial. In an experiment, six layers of copper were deposited along a 15mm length and deposition rates were calculated by measuring the weight of the work piece before and after the deposition. The work piece was weighed on an Afcoset electronic balance model no: ER-182A with a resolution of 10 micrograms and a maximum limit of 32 grams. The experiment was carried out with open loop as well as closed loop control to compare the effect on deposition rates and deposit quality in terms of volume fraction. The volume fraction of the deposit is evaluated by studying the volume fraction of the deposit at three cross sections (one at the centre and other two near the ends) and then calculating the average of them. This gives a fair idea about the average volume fraction of the deposit at a particular combination of parameters. The micrographs were taken through a Carl Zeiss Axiovert 40MAT microscope using a PixeLINK PL-A662 camera at 1000X magnification. They are analysed using eMpower Metallographic Image Analysis software to obtain the volume fraction of each cross section.

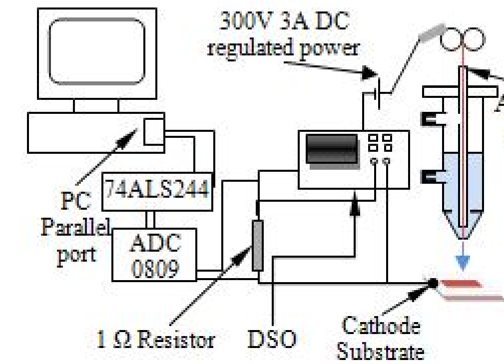

Fig. 4: Connection of ADC to the experimental set up

B. The control algorithm and conditions imposed on the control system

The focus of the algorithm is to maintain the current levels in the ICWF for a given set of process parameters. This indirectly maintains the periodicity and shape of ICWF for that combination of process parameters. The terms used in the development of the algorithm are illustrated in Figure 1. C_U and C_L are the upper and lower limits respectively, of the acceptable range of C_{AMP}. C_S is the set current which the algorithm tries to maintain in the T_{ON} interval. The nozzle tip is always positioned at the required SOD with respect to the unprocessed surface of the substrate. Before switching on the power supply, the wire tip is brought to the nozzle tip manually. As the SOD in this condition is correct, the first measured value of current after switching on the power, is taken as C_S value for the particular combination of parameters. If current goes below C_D= 8 mA, the algorithm considers it as T_{OFF} region. The value of C_D is decided based on the resolution of the ADC, which is 3.9 mV per step. The value of C_D is taken to be about two steps of the ADC's measurable values. If the slope of the ICWF becomes more than 100 mA/ms, the algorithm considers it as the T_T region. The measured feedback current is 'C_F' in mA. If the C_F is above C_D and if the slope of ICWF is less than 100mA/ms, the control system considers it as T_{ON} phase. The objective of the control system is to detect the different events occurring during the process and respond by controlling the wire feed rate. The objectives, the events and the action taken by the closed loop control system are listed in table I. The set values of C_U and C_L were determined by trial and error. When C_U - C_S= C_S- C_L=8 mA was applied, it was observed that wire tip remained flush to the nozzle tip. As explained earlier, this condition cannot achieve a control over the instantaneous SOD due to metal pile formation. Hence the conditions C_U - C_S =0 and C_S - C_L=4 were arrived at to obtain the required results. The algorithm uses a combination of discrete event control system and a proportional controller to vary or maintain the wire feed rate. It can be noticed in Fig.1 that the current is much less than C_S at T_T and T_{OFF}. If a continuous proportional controller alone is used, the algorithm should increase the wire feed rate at T_T and T_{OFF} in order to reduce the SOD and bring the current level back to C_S. To maintain the periodicity of ICWF, T_{OFF} is essential where wire dissolution does not take place. In the transition period, T_T the current falls very rapidly to zero where the gradient of current wave form is more than

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100mA/ms. Hence the wire feed should be stopped in both these phases to maintain SOD. In order to meet these objectives, the Discrete event control system detects the events occurring in the process, listed in table I, and then executes the corresponding action. The events 4 and 5 trigger the proportional controller to change the wire feed rate. The proportional controller algorithm calculates the error in wire feed as follows:

$$Err = kp * (C_F - C_S) \ \ ms \qquad (1)$$

Where Err = Correction in the wire feed delay in ms, recalculated in every 500 µs; kp = Proportional constant (ms/mA) . This was decided to be 1.5ms mA^{-1} by trial and error; (C_F - C_S) = error in measured current from set current value in mA. Fig 5 illustrates the control algorithm. The programming is done in C-language. The program works in a continuous loop and each cycle of the loop completes in 500 µs. This is achieved by adjusting the time delay function in the loop and calibrating it by monitoring the output pulses to the stepper motor controller (SMC) using a Digital Storage Oscilloscope (DSO). This timing of the cycle is decided considering the fact that T_{ON} and T_{OFF} are in the range of 1-15 ms. The feedback of current is taken by the ADC in every cycle of the loop. The difference in consecutive readings of current is calculated in every cycle to determine the instantaneous slope of the waveform. If this value increases above 100mA/ms the algorithm decides that it is the T_T phase.

III. Results and discussions

Periodic ICWF is the characteristic of FDED which comprises of T_{ON}, T_{OFF} and spikes due to discharge. In open loop systems, the metal pile ups can take place due to many reasons such as residence time of the jet at a location depending upon the table speed, limitations of the set up etc. These effects lead to the change in SOD. And the effect is further magnified when deposition is done on a pre-deposited layer. The current tends to increase over the peaks on the undulations and decrease at the valleys. In such a situation, ICWF can not be maintained. This affects the deposition rate as well as the volume fraction of the deposit. Hence the effects of the feedback control system on the ICWF, deposition rate and volume fraction have been investigated.

Table I

Objectives, events and Actions taken by control system

Objectives	Events	Action taken
To detect whether the current is in T_{ON}, T_{OFF} of T_T.	--	The criterion – explained in IIB.
To maintain the SOD when the value of current in T_{ON} region is between C_U and C_L	Event 1: $C_U>C_F>C_L$ C_F in T_{ON} region	Desirable condition, Hence maintain wire feed rate.
To stop the wire feed whenever it detects T_{OFF} as there is no electrochemical reaction in this region.	Event 2: $C_F< C_D$	Stop wire feed.
To stop the wire feed when current is in T_T region as this is a transition phase.	Event 3: C_F in T_T region	Stop wire feed.
To cause increase in SOD when current increases beyond C_U, as this would indicate an unacceptable decrease in SOD.	Event 4: $C_F >C_U$	Stop wire feed. Recalculate and decrease the wire feed.
To reduce SOD when current is between C_L and C_D because this indicates an increase in SOD than required.	Event 5: $C_L>C_F>C_D$ and not in T_T region.	Recalculate and increase wire feed

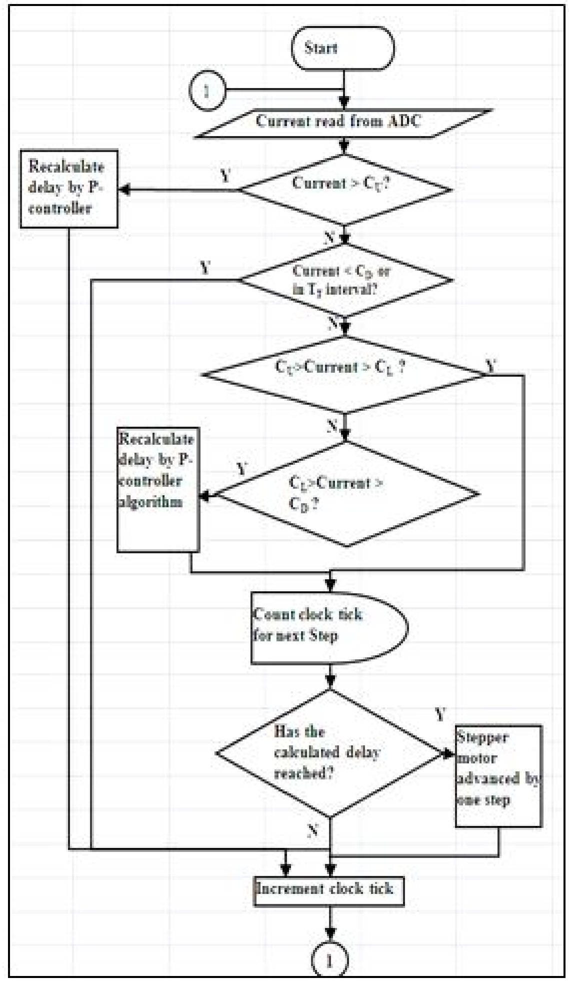

Fig.5: Flow chart of the control system

A. Effects on ICWF

Fig. 6 shows the ICWF when the process was with an open loop control. The process parameters are 160V, 3mm SOD with a flow rate of $273mm^3s^{-1}$. Though periodic, it has a lot of undulations in the T_{ON} region, the durations of T_{ON} and T_{OFF} change in each cycle, changing the frequency. Fig 7 shows the ICWF of an FDED process controlled using feed back control at 160V, 4 mm SOD and $273mm^3s^{-1}$. It can be observed that the periodicity of the ICWF and consistency of current in the T_{ON} region has fairly improved as compared to the one in Fig. 6. Fig. 8 shows an ICWF when the feedback control system responds to a detection of Event 5 at point A. The process parameters are: voltage=150V and SOD=4mm, C_S =104mA. The feed back system measures the current to be 50 mA at point A. The current at this point is much lower than C_S because it corresponds to phase 3 illustrated in fig.2, where the SOD has increased. At this point of time, the controller increases the wire feed to reduce the SOD. This increases the current, bringing it to 85mA at point B and 96mA at point C and finally to the C_S value at D. It takes 5.3ms to bring the current from point A to the set value. Any further increase in current above C_S after the point D will be inhibited by the control system by stopping the wire feed and recalculating the wire feed delay until the current in the T_{ON} region is maintained within 100 and 104 mA.

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As seen in Fig. 8, the controller takes 5.3 ms to bring the current at point A (50mA) to the set value of 104mA mainly due to the limitations of the experimental set up. The wire feed stepper motor can change the SOD only in the steps of 0.013mm. Hence any change in current through the control of SOD can take place only in increasing steps of current values corresponding to 0.013mm change in SOD. Hence the factor 'kp' in equation 1 has to be determined such that the current does not overshoot above C_S due to a high rate of change of SOD during feedback control. The value of kp, reduced to avoid overshooting of current, in turn increases the response time. Secondly, occasional minute slippages noticed between the wire feeding rollers and the wire reduce the feed rate. Furthermore, the calculated delay between steps of the wire feed stepper motor is always above 10ms, where as the events detected in the ICWF occur mostly within a

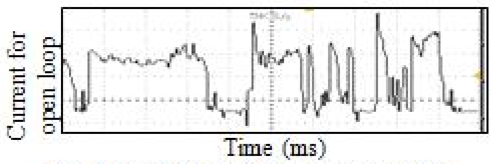

Fig. 6: ICWF for open loop control system

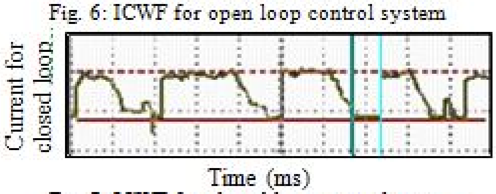

Fig. 7: ICWF for closed loop control system

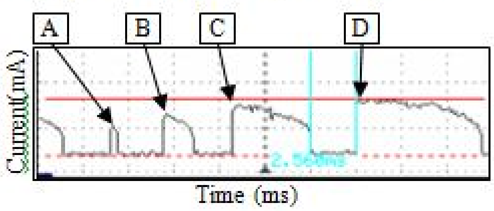

Fig. 8: Current control at SOD= 4mm, Voltage=150V and Set current= 104mA

range of 5ms. The solution to this would be to incorporate high speed stepper motors with smaller step angles coupled with higher gear reduction ratio, so that faster changes in wire feed can be done in smaller wire feed step increments. The effect of this would be higher resolution and shorter response time. The response of the program to the changes in the electrolyte flow rate due to physical limitations of the experimental set up, mentioned previously, is similar to that when SOD changes. An increase in flow rate increases the electrochemical reaction and hence the current. The program responds to this by reducing the wire feed rate and thereby increasing the SOD. A decrease in flow rate is responded by a reverse effect.

B. Effects on Deposition rate

Fig. 9 compares the experimentally determined deposition rates when the process is controlled in closed loop and open loop mode. All the graphs except E and I reveal that the deposition rate in general has increased by 5 µg/s with the feedback control, as compared to that without feedback control. They also reveal that the deposition rate increases up to a certain value of voltage and then decreases.

In FDED process, variations in ICWF directly affect the deposition rate as the electrochemical deposition varies directly with the values of C_S and T_{ON}. At the same time energy released by the discharge during T_{OFF} determines whether the deposition fuses to the substrate or gets eroded. The high energy discharges erode the deposit and feeble discharges do not fuse the deposit to the substrate. The increase in current above limiting current leads to powdery deposit which flows away with the electrolyte. Since the closed loop control maintains the ICWF fairly, despite the undulations in the pre deposited layer and the variations in the process parameters, it leads to fairly consistent deposition rate which is more than that in the open loop control. The electrochemical deposition and fusion due to discharge, have additive effect to the deposition rate till a certain voltage depending upon the combination of process parameters. Once this voltage is exceeded, the periodic ICWF becomes transient reducing electrochemical deposition. Moreover, the discharges at high voltage erode the deposit owing to their high power. Hence after reaching a maxima at a particular value of voltage the deposition rate decreases. In the case of graphs E and I, the deposition rate continuously increases with in the range of the decided operating voltage, indicating that the maxima has not reached at the studied values of voltage. Hence in these cases, by keeping the operating parameters (other than voltage) constant the optimum combination of process parameters leading to maximum deposition rate is expected to reach at higher voltage values than the studied ones.

C. Effect on volume fraction

Table II reveals, that the volume fraction of deposits at different combination of process parameters, increases

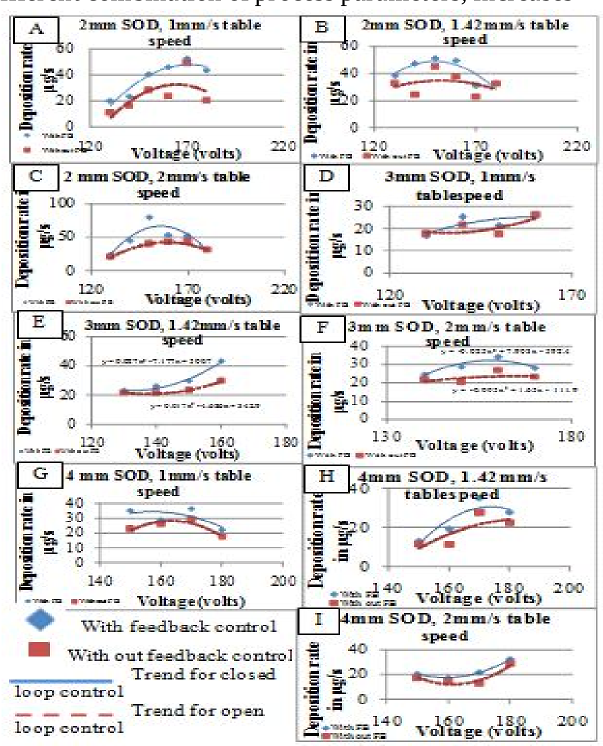

Fig.9: Comparison of deposition rates with Feedback control and without feedback control. Deposition rate Vs Voltage graphs at different SOD-s and table speeds

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by an average of 12%, when the system is under feed back control as compared to those with an open loop system. The increase in volume fraction is a direct result of uniform distribution of the deposition by maintaining ICWF and avoiding unnecessary pile ups and subsequent discontinuities. The effect of pile up explained in Fig 2 was predominant with the table speeds of 1mm/s and 1.42 mm/s. The volume fraction decreases with voltage, in case of above two table speeds, which does not happen with the table speed of 2mm/sec. The table speed itself is a parameter that can avoid pile up and assist feedback control system, by distributing the deposition on the larger area.

IV. Conclusions

The previous studies have established that the periodic ICWF is the characteristic of FDED process and particular combination of process parameters results in a particular frequency and shape of ICWF. If process parameters are properly controlled the form of ICWF can be maintained. But the limitations of the experimental set up cannot control the parameters precisely. In the present study, an attempt has been made to maintain the current level in T_{ON} of an ICWF by implementing the closed loop control to maintain SOD. This also takes care of variations in the electrolyte flow rate by varying the tool feed rate. This improved the deposition rates by 5µg/s and deposit characteristics in terms of volume fraction by almost 12%. Hence it can be said that the feedback control has been fairly successful in controlling the process.

TABLE II.
Volume fraction of FDED specimens

SOD in mm	Voltage (volts)	Table speed mm/s	Volume fraction for open loop control	Volume fraction for closed loop control
3	140	1	44.684	57.306
3	150	1	42.478	55.168
3	160	1	34.760	51.140
3	140	1.42	38.297	50.950
3	150	1.42	35.134	48.898
3	150	2	26.600	35.590
3	160	2	39.190	45.980

The present algorithm attempts to control periodicity and shape of the ICWF indirectly by maintaining C_S. The direct control of ICWF, by maintaining T_{ON} and T_{OFF} using a higher resolution ADC with lower processing time may further improve the results. The process will result in improved deposition rate if run at optimum combination of process parameters. The effectiveness of the feedback system can be improved by increasing resolution and reducing response time of wire feed by using high speed stepper motor coupled with higher gear reduction ratio. Introducing a lapping process in between the deposition of two layers can increase the effectiveness of the feedback system as the control system doesn't have to take care of huge undulations which make the present algorithm ineffective especially at lower table speeds.

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